Global climate change and US agriculture

Richard M. Adams*, Cynthia Rosenzweig†, Robert M. Peart‡, Joe T. Ritchie§, Bruce A. McCarl||, J. David Glyer¶, R. Bruce Curry‡, James W. Jones‡, Kenneth J. Boote & L. Hartwell Allen, Jr††**

* Department of Agricultural and Resource Economics, Oregon State University, Corvallis, Oregon 97331, USA
† Goddard Institute for Space Studies, Columbia University, New York, New York 10025, USA
‡ Department of Agricultural Engineering, University of Florida, Gainesville, Florida 32601, USA
§ Department of Crops and Soil Science, Michigan State University, East Lansing, Michigan 48824, USA
|| Department of Agricultural Economics, Texas A&M University, College Station, Texas 77843, USA
¶ Christensen and Associates, 4610 University Ave., Madison, Wisconsin 57305, USA
** Department of Agronomy, University of Florida, Gainesville, Florida 32601, USA
†† USDA-ARS, Department of Agronomy, University of Florida, Gainesville, Florida 32601, USA

Agricultural productivity is expected to be sensitive to global climate change. Models from atmospheric science, plant science and agricultural economics are linked to explore this sensitivity. Although the results depend on the severity of climate change and the compensating effects of carbon dioxide on crop yields, the simulation suggests that irrigated acreage will expand and regional patterns of US agriculture will shift. The impact on the US economy strongly depends on which climate model is used.

CARBON dioxide concentration of the atmosphere has increased from ~280 p.p.m. before the industrial revolution to ~350 p.p.m. today[1]. According to most climate models, a continued build-up of CO_2 and other infrared-absorbing 'greenhouse' trace gases is likely to lead to surface air temperature rises of 1.5–5.5 °C and changes in precipitation patterns over the next 50–75 years[2-7]. Climate changes of the magnitude suggested by climate models will have agricultural consequences. Many authors have presented qualitative discussions on these agricultural implications[8-10], but quantitative estimates of changes in crop yields and irrigation water use and the resulting effects on producers and consumers have not appeared.

Here we report the results of a multidisciplinary study using global climate models, crop-growth models and an economic model to estimate effects of possible CO_2-induced climate change on US agriculture. Although this research provides quantitative estimates of potential effects on the agricultural economy, perhaps the main contribution is highlighting uncertainties in current knowledge. For example, differences in average seasonal temperature and precipitation between two climate model forecasts result in substantial differences in crop yields and irrigation water requirements in some regions of the US. The effect of these and other uncertainties on the economic assessment is one means of finding priorities for future research.

Another contribution is recognition of the value of integrating models from various disciplines, here atmospheric science, agronomy and economics. Although interdisciplinary efforts of this kind are encouraged[11-13], it is stressed that the results of such an integrated approach do not predict the future; rather, evaluation of results offers insights into effects of the hypothesized conditions (here, CO_2-induced climate change) on a system (here, the US agricultural economy) as it is currently understood. These insights may then contribute to the larger societal policy discussion of both potential control strategies to reduce CO_2 and other trace-gas emissions and on appropriate strategies to prepare for change.

TABLE 1 Summary of climate change in GCMs for doubled CO_2: average of US grid points

	Temperature change (°C)			Precipitation change (mm day^{-1})		
Model	Annual	Winter	Summer	Annual	Winter	Summer
GISS	+4.32	+5.46	+3.50	+0.20	+0.13	+0.24
GFDL	+5.09	+5.25	+4.95	+0.09	+0.19	−0.08

Source: ref. 30.

Effect of CO_2 increases on US climate

A number of global-climate research projects have calculated likely climate changes under alternative CO_2 levels using numerical models of the atmospheric general circulation known as GCMs[7]. The forecasts used here are from the NASA/Goddard Institute of Space Studies (GISS) model[14] and the Princeton Geophysical Fluid Dynamics Laboratory (GFDL) model[5]. Ratios of mean monthly temperature, precipitation, and incident solar radiation for doubled CO_2 (to 630 and 600 p.p.m. respectively) simulations to current climate simulations were applied to observed (1951–1980) daily station climate variables. Observed variables at individual locations were multiplied by ratios of climate change from the appropriate GCM gridbox (8° lat. × 10° long. for GISS; 4.5° lat. × 5° long. for GFDL). No interpolations were made between or within grid boxes because GCM calculations do not account for this variation. The calculation of the GISS and GFDL climate-change models does not

TABLE 2 Derived climate parameters of selected agricultural regions as predicted by GISS and GFDL

	Evaporation ratio†		Precipitation ratio†		Average annual temperature increase (°C)	
Region*	GISS	GFDL	GISS	GFDL	GISS	GFDL
Southeast	1.08	0.93	1.11	0.92	3.5	4.9
Delta	1.02	1.02	1.02	1.00	5.3	4.4
Northern Plains	1.09	0.99	1.07	0.97	4.7	5.9
Southern Plains	0.99	1.02	0.92	1.00	4.4	4.5
Mountain	1.10	1.06	1.11	0.99	4.9	5.3
Pacific	1.11	1.03	1.15	1.02	4.7	4.7

Source: ref. 30.

* The southeast region includes Florida, Georgia, South Carolina and Alabama; Delta region includes Arkansas, Louisiana and Mississippi; Northern Plains are Kansas, Nebraska, North Dakota and South Dakota; Southern Plains are Oklahoma and Texas; Mountain region includes Arizona, Colorado, Idaho, Montana, New Mexico, Nevada, Utah and Wyoming; Pacific region includes California, Oregon and Washington.

† Evaporation ratio is the doubled-CO_2 forecast for evaporation relative to the current-CO_2 forecast.

‡ Precipitation ratio is the doubled-CO_2 forecast for precipitation relative to the current-CO_2 forecast.

include changes in the space and time distribution of climate events. Therefore many significant climate and biophysical features are ignored. Forecasts of annual as well as seasonal temperature and precipitation changes are summarized in Tables 1 and 2. The use of two GCM models reflects some of the variation in climate estimates. For example, both models forecast increases in regional temperature but differ on changes in precipitation and evaporation. Table 2 points out the lack of consensus for some important agricultural regions, an issue that has implications for assessing climate-change effects[7,15].

It should be stressed that the doubled-CO_2 model represents an equilibrium climate, rather than one responding transiently to the gradually increasing trace-gas forcing. Because other trace greenhouse gases (for example, CH_4, N_2O, chlorofluorocarbons) are increasing, the climate-change models may be considered to be an 'effective' doubling of CO_2, meaning that the radiative forcing of all greenhouse gases has the same radiative forcing as doubled CO_2. The effective doubling of CO_2 concentrations will occur around the year 2030, if present emission trends continue[4]. The climate change caused by this effective doubling may be delayed, owing to slow uptake of heat by the oceans and other factors. A more detailed discussion of these and other uncertainties is presented by Schneider[7].

TABLE 3 Predicted percentage change in irrigated-crop water use requirements and water supply for irrigated regions*

Region	Irrigated-crop water use GISS	GFDL	Supply†‡ GISS	GFDL
Southeast	15	147	16.0	−9.0
Delta	16	60	2.0	−3.0
Northern Plains	−13	14	1.0	−3.0
Southern Plains	−4	−10	−3.0	−2.0
Mountain	−8	2	2.0	−7.0
Pacific	−9	3	7.0	−2.0

* Regions are defined in Table 2.

† Water availability in areas that currently do not rely on irrigation is not addressed in these analyses. These excluded areas contain <3% of current (1985) irrigated acreage.

‡ Changes in water supply are calculated using base weather, precipitation (ratios) and evapotranspiration (ratios). Specifically, the percentage change in water supply is calculated as $\%\Delta(WS) = [(BP \times PR) - (BE \times ER) - BWS]/BWS \times 100$ where WS, water supply; BP, base precipitation; PR, precipitation ratio (forecast precipitation/base precipitation); BE, base evaporation; ER, evapotranspiration ratio (forecast evaporation/base evaporation); and BWS, base water supply (BP − BE).

Physical effects on the agricultural system

Crop yield effects. The climate changes described in Tables 1 and 2 are expected to lead to changes in crop yields, but substantial resources and time would be needed to perform experiments to explore even part of the range of these variations. In this study, the SOYGRO (version 5.41)[16], CERES-Maize[17] and CERES-Wheat[18] dynamic-growth crop-simulation models are used to project the effects of climate changes on the yields of irrigated and rainfed winter wheat, maize (corn) and soybeans[19-21]. The choice of these widely validated models is based on several criteria. First, the models simulate crop response to the major climate variables of temperature, precipitation and solar radiation, and include the effects of soil characteristics on water availability for crop growth. They are also physiologically oriented, with functions that calculate the rates of photosynthesis, translocation, respiration and other crop processes. Growing-degree days and photoperiod effects are modelled for the three crops. Second, they are validated for a range of soil and climate conditions. Third, these models are developed with compatible data structures so that the same soil and climate data bases could be used with all crops. An important issue in assessing agricultural effects of climate change is the role of elevated CO_2 on plant growth[22,23]. Increased CO_2 has been found to increase photosynthesis and decrease stomatal conductance in most crop plants in experimental settings, resulting in reduced transpiration rate per unit leaf area and overall increase in water-use efficiency (seed yield divided by total evapotranspiration during the growing season (kg ha^{-1} mm^{-1}))[23,24]. Modifications to the crop models were made to calculate photosynthesis and evapotranspiration rates under increased CO_2[19-21]. Photosynthetic rates were increased by 35, 25 and 10% for soybeans, wheat and maize, respectively, under doubled-CO_2 conditions.

Limitations of the crop models. Although the crop-simulation models were developed and tested over a range of climate conditions, they have not been tested under the temperature conditions suggested by the GCMs. The crop models also assume that soil nutrients are not limiting, there are no other major soil problems, and that pests (insects, diseases, weeds) pose no limitation to crop growth and yield. Further, the beneficial effects of CO_2 on crop yields will be overestimated if the equivalent warming of the doubled-CO_2 climate occurs before an actual doubling of atmospheric CO_2 (due to increases of other greenhouse gases) and if the experimental results are not reproduced under warmer, more variable and pest-infected field conditions. Finally, changes in climate variability, which were not simulated, could significantly alter the results. If frequency of droughts or mesoscale convective complex (MCC) rainfall and hail damage increases, climate-change effects on crop yields could be more severe[25].

Crop yield results. Rainfed-crop yield estimates shown in Fig. 1 differ markedly for the two GCMs, even though the annual average changes shown in Table 1 are not very different. Crops are sensitive to weather over relatively short periods of time, and annual averages do not convey important shorter-term differences. For example, consider the average monthly growing season precipitation for one location, Columbia, South Carolina. The historical average for June is 113 mm. For the doubled-CO_2 analysis, the models differ sharply in monthly precipitation forecasts, with GISS forecasting 148 mm and GFDL 50 mm. The lower summer growing-season precipitation for the GFDL model accounts for its much lower yields under rainfed conditions.

The simulated changes in crop yields are driven by two effects, changes in climate and CO_2 enrichment. The interaction of these forces leads to predictions that vary by region. In more northern latitudes a longer frost-free growing season and increased temperatures had a beneficial effect on simulated yields. In other regions, high temperatures shortened the duration of crop growth stages, especially grain-fill, resulting in moderate to severe yield decreases[19-21]. The beneficial effects of elevated CO_2 on crop yields, however, offsets some or all of the adverse climate effects. As a result, average yields in most regions actually increase in the milder GISS climate-change model, whereas a pattern of yield decreases persists in the hotter and drier GFDL model. Irrigated yields tend to be higher and less variable than rainfed yields, in both the base-period and climate-change scenarios[19-21].

In regions where present crop yields are relatively low, high percentage increases in yields do not indicate large absolute increases in crop yields. For instance, the Lake States and Northern Plains regions currently have low relative average yields based on 1951–1980 climate, so these increases may not be as significant as the smaller percentage increases in the higher-yielding Corn Belt. Similarly, for the Southern Plains, Mountain, and Pacific regions, changes in maize yields for rainfed production are not as important as changes under irrigation, because the majority of the production from these regions is from irrigated land.

Irrigation water use and availability. Rising temperatures in Tables 1 and 2 suggest increased evapotranspiration, crop water use and irrigation demand. The CERES and SOYGRO models calculate the irrigation water applied by irrigating the soil profile up to field capacity whenever the crop becomes water-stressed. Changes in irrigated-crop water-use requirements are presented in Table 3. The irrigation water use values reported in Table 3 for the GISS and GFDL models are used to adjust irrigation water requirements in the economic model of the agricultural sector. Changes in water use vary with GCM models, with modest increases or slight decreases under GISS but substantial increases projected under GFDL in the southern United States.

Changes in ground- and surface-water availability are estimated using a simple hydrologic mass-balance approach that reflects the interactions of evaporation, rainfall and temperature forecasts from the GCMs (Table 3). If a region currently has greater annual precipitation than annual potential evaporation, the same percentage increase in evaporation and precipitation could increase the differential, suggesting an increase in runoff. Predicted changes in regional water supply that reflect these estimates are reported in Table 3. Note that GFDL projections are much more severe than GISS, showing water-supply reductions in all irrigated regions, caused by increased evaporation driven by high temperatures. The procedure used to calculate regional changes are described in Table 3. Assumptions underlying forecast changes in agricultural water availability are discussed by Adams, Glyer and McCarl[26].

Economic consequences. The final step in the assessment involves adjustments in the parameters of an economic model of the US agricultural sector to reflect the crop yield, water use and water-supply effects of climate change. A correct translation of these effects into their implications for societal well-being requires a model that reflects the adjustments that producers, consumers and other affected parties are likely to take to soften the impacts of adverse climate[12]. Thus, human behavioural responses to adverse climate must be modelled.

The economic model is one previously used in a number of appraisals[27-29] and is designed to simulate the effects of changes in agricultural demand, resource usage or resource availability on agricultural prices, quantities produced, consumers' and producers' welfare, exports, imports and food processing. The model considers production, processing, domestic consumption, imports, exports and input procurement for most crop and livestock commodities. Included are both primary commodities (those produced directly by farms) and secondary commodities (activities such as soybean crushing and livestock feeding and processing).

A total of 1,683 production possibilities are specified to represent major field crop and livestock production in the United States. For some regions, field crops are divided into irrigated and non-irrigated production. Each crop and livestock

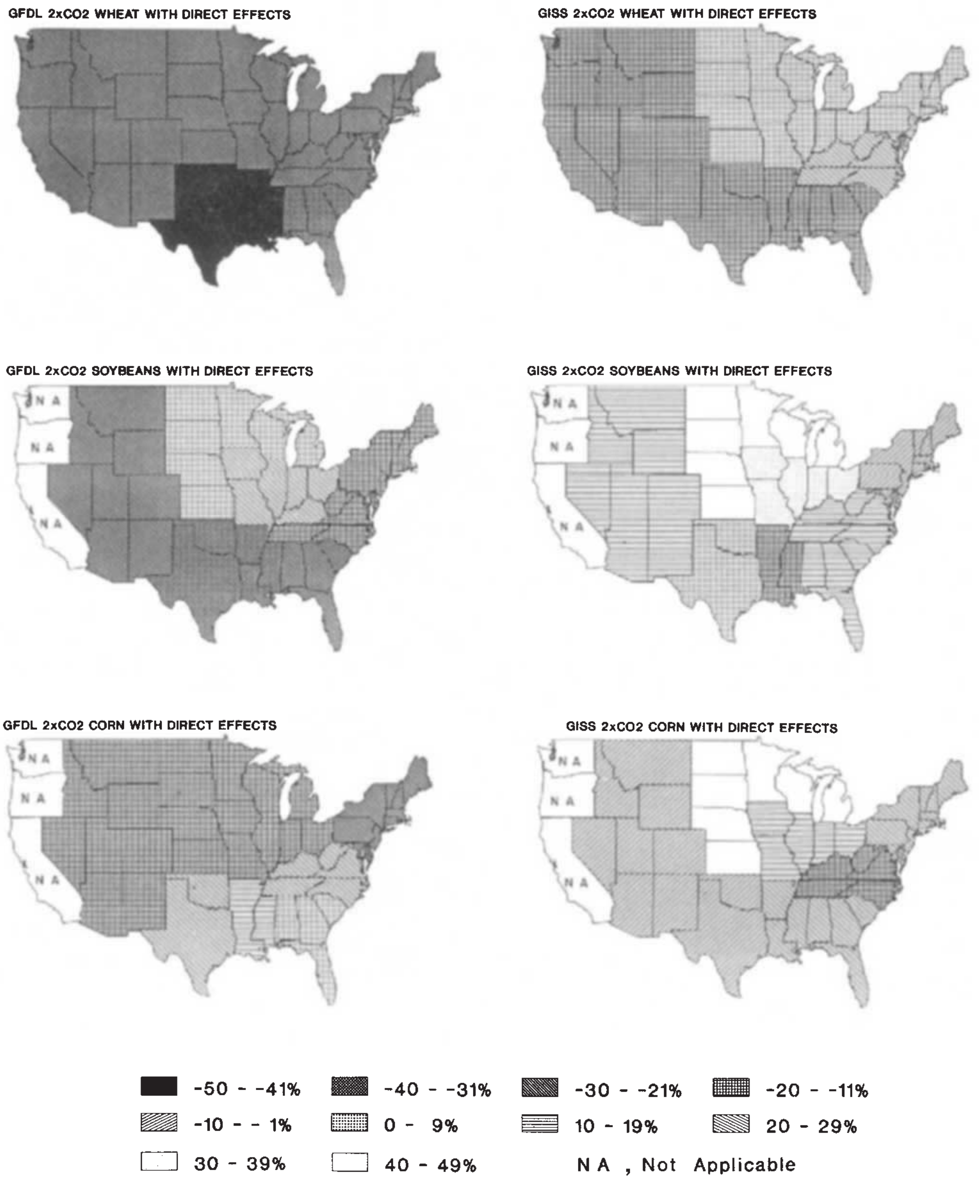

FIG. 1 Percentage change in rain-fed crop yields simulated by the SOYGRO, CERES-Maize, and CERES-Wheat models modified for the direct effects of CO_2 on photosynthesis and transpiration using GISS and GFDL doubled-CO_2 climate-change models. Soybeans and corn were modelled at sites in the following states: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, Michigan, Ohio, New York, Pennsylvania: winter wheat and corn were modelled in Nebraska, Kansas, Oklahoma and Texas. Results were extrapolated to other sites on the basis of similarity of current-climate growing conditions.

TABLE 4 Estimated economic consequences of climate change on US agriculture

Model/analysis	Effect: Consumers	Effect: Producers	Effect: Total	Change from base: Consumers	Change from base: Producers	Change from base: Total
	(thousand million 1982 $)					
Base (1981–83 climate, demand and technology)	77.32	17.80	95.12	—	—	—
GISS with doubled CO_2	86.62	19.39	106.01	+9.30	+1.59	+10.89
GFDL with doubled CO_2	63.44	21.35	84.78	−13.89	+3.55	−10.33

production activity requires information on yields and usages of inputs or other commodities. This information is from the 1982 United States Department of Agriculture (USDA) Farm Enterprise Data System (FEDS) budgets, the USDA survey of irrigated acreage, Extension budgets, and Soil Conservation Service (SCS) budget sets.

Production is simulated in 64 geographical subregions distinguished by resource endowments. These areas are then grouped into ten larger regions for purposes of land, labour and water supply. The water resource is of particular interest here and is disaggregated into surface and pumped ground water sources. Surface water is available for a constant price within each region, but pumped ground water is provided according to a supply schedule where increasing amounts of water are available for higher prices.

The production and consumption sectors are assumed to be made up of a large number of individuals operating under competitive market conditions. This leads to a model that maximizes the difference between the areas under the demand and supply curves. This area can be interpreted as a measure of economic welfare (ordinary consumers' plus producers' surplus) equivalent to the annual net income (in 1982 dollars) lost or gained by agricultural producers and consumers (both domestic and foreign) as a consequence of climate change. The model is solved as a quadratic programming problem. A more detailed description of the model is found in Cheng and McCarl[27].

Economic model simulations

Adjustments in crop yields, irrigated-crop water requirements and irrigation water availability were made in the economic model according to each GCM forecast (Fig. 1 and Table 3). In addition to the modelled crops (maize, wheat, soybeans), the yields for cotton, barley, grain sorghum, rice and alfalfa were adjusted (by the average yield changes of the modelled crops) based on similarity of current-climate growing conditions. Inclusion of these other major crops is needed to account for potential substitution of crops within and across regions and to reflect the role of such crops in livestock production. A model solution is then generated to see how climate change and elevated CO_2 might alter the economics of the agricultural sector relative to a hypothetical 'no climate change' case.

Three solutions were generated with the economic model. These include the yield and water manifestations of each climate-model forecast and a base solution of the 1981–83 economic model. The direction and magnitude of the changes in income, crop acreage and other modelled characteristics between the base and the climate-change solutions indicate potential economic and resource implications (in quantitative terms) of each climate scenario.

Results from the economic model

The economic consequences of climate change are dependent on the GCM projections. This can be seen in Table 4 where annual aggregate effects on consumers and producers range from a net gain of over $10,000 million (GISS) to a loss of over $10,000 million (in 1982 dollars) for GFDL. These estimates are ~8% of the 1982 market value of US crop and livestock production. The GFDL losses are driven by the yield losses shown in Fig. 1 and the substantial increases in irrigation water requirements associated with adverse climate change. (Without the mitigating effect of CO_2 on crop yields, economic losses under GFDL would increase threefold[26].) Note that the change in producers' income is positive under GFDL because of prices rising by more than the climate-induced reduction in total production (that is, inelastic demand). Producers in some regions do lose, however, as regional production declines by more than the increase in prices.

Under the GFDL climate-change model, crop prices increase from reduced production of some crops. These price increases work against consumers, whose losses are greater than the gains to producers reported in Table 4. Aggregate price and quantity adjustments for crops and livestock commodities, expressed as indices (weighted by the quantities of each crop), are reported in Table 5. Price changes are slight to moderate across the climate-change projections. GISS yield (increases) and water forecasts result in price declines of 17 and 16% for eight field crops and four livestock commodities, respectively. These price declines are the result of 9 and 6% increases in agricultural output for each group. For GFDL yield and water changes, prices increase by 34 and 8% for the same set of commodities, due to production reductions of 20 and 2% for crops and livestock.

For perspective, we compare these aggregate economic consequences of climate change and elevated CO_2 to the economic effects of other environmental stresses. The economic consequences of anthropogenic tropospheric ozone on US agriculture have been estimated to be $2,000–$3,000 million per year in 1982 dollars[28] whereas the estimates of a 15% depletion in the stratospheric ozone column amount to ~$2,500 million[29]. Thus, the agricultural consequences of climate change under GFDL imply potential economic costs four times greater than these other environmental stresses.

A major policy concern is whether climate change is a food security issue for the United States. The results of these analyses suggest that it is not. For GFDL, the capacity of the US agricultural system to produce food and fibre is reduced, but under GISS production actually increases. US consumers face moderately higher prices under a GFDL climate-change model and the movement of US production into export markets is reduced. Indeed, almost half of the consumers' losses arising under the GFDL climate change accrues to foreign consumers. The analysis here, however, does not consider changes in agricultural production due to climate change in other countries.

These simulations were derived from an economic model based on 1981–83 economic and agronomic conditions. As the full extent of the climate changes projected here will not occur for decades, the sensitivity of the economic estimates were tested

TABLE 5 Agricultural commodity price and quantity indices* for climate-change models (base = 1.00)

Climate model	Field crops† Price	Field crops† Quantity	Livestock commodities‡ Price	Livestock commodities‡ Quantity
GISS with doubled CO_2	0.83	1.09	0.84	1.06
GFDL with doubled CO_2	1.34	0.80	1.08	0.98

* Indices reported here are Fisher indices, where $P=[(\mathbf{p}^1\cdot\mathbf{q}^1/\mathbf{p}^0\cdot\mathbf{q}^1)(\mathbf{p}^1\cdot\mathbf{q}^0/\mathbf{p}^0\cdot\mathbf{q}^0)]^{1/2}$, $Q=[(\mathbf{p}^1\cdot\mathbf{q}^1/\mathbf{p}^1\cdot\mathbf{q}^0)(\mathbf{p}^0\cdot\mathbf{q}^1/\mathbf{p}^0\cdot\mathbf{q}^0)]^{1/2}$, and where $\mathbf{p}^0(\mathbf{q}^0)$ and $\mathbf{p}^1(\mathbf{q}^1)$ are vectors of prices (quantities) in the original and final equilibria, respectively[3].

† Field crops include maize, wheat, soybean, sorghum, cotton, oats, hay (alfalfa and grass hays) and silage.

‡ Livestock commodities include poultry, pork, beef and milk products.

TABLE 6 Effects of climate change on irrigated and rain-fed crop acreage

Region*	Base acreage			GISS, change from base			GFDL, change from base		
	Irrigated	Rain-fed	Total	Irrigated	Rain-fed	Total	Irrigated	Rain-fed	Total
Corn Belt	NA	95.46	95.46	NA	+1.53	+1.53	NA	−4.93	−4.93
Lake States	NA	33.79	33.79	NA	+0.14	+0.14	NA	+3.40	+3.40
Southeast	1.72	10.79	12.51	−0.06	−3.78	−3.84	−0.16	−4.52	−4.68
Delta	3.11	16.77	19.88	+1.08	−11.68	−10.60	+5.91	−9.09	−3.18
Northern Plains	10.28	91.40	101.68	+3.94	−1.12	+2.82	+4.03	−2.14	+1.89
Southern Plains	5.31	49.4	54.70	+1.50	−12.40	−10.90	−0.60	−1.90	−2.50
Mountain	16.14	5.54	21.68	−2.69	+1.46	−1.23	+0.02	−0.27	−0.25
Pacific	7.73	1.94	9.67	−0.21	+1.03	+0.82	+0.26	+0.95	+1.21
Other (Northeast and Appalachian)	NA	19.54	19.54	NA	−5.68	−15.68	NA	−8.76	−8.76
	44.29	324.63	368.92	+3.56	−40.50	−36.94	+9.46	−27.26	−17.80

* Corn Belt region includes the states Illinois, Indiana, Iowa, Ohio and Missouri; Lake States include Michigan, Minnesota and Wisconsin; other regions defined in Table 2. NA, not applicable.

by changing demand and technology parameters in the economic model. Specifically, US domestic and export demands were increased to reflect increases in US and world population, and yields were increased based on historical per annum yield changes, projected until 2050. Increases in domestic and foreign demand increased economic losses for the GFDL climate model. Conversely, technology (through increased yields) offsets the climate-induced losses reported in Table 4 for GFDL if yields increase at rates comparable to the last three decades. Although such yield increases offset the effects of adverse climate, climate change still imposes economic costs (in the form of foregone higher yields in the absence of climate change).

Effects on regional production, irrigated acreage and the environment. Climate change leads to a slight reduction in total US cropped acreage. Aggregate (and regional) acreage adjustments are presented in Table 6. Under GISS, aggregate acreage is reduced due to increased yields. For GFDL, acreage is reduced owing to shifts in production between regions and associated changes in resource availability. Both analyses show reductions in aggregate rainfed acreages. Included are some potentially large regional adjustments, driven by the regional variations in climate change. For example, north or northwest shifts in acreage and production occur for some commodities (Table 6). This implies increased input demands in areas of expanded crop acreage, such as the Pacific and Lake State regions, and corresponding reductions in regions experiencing acreage declines, such as the southeast and Southern Plains. Shifts in regional production patterns imply changes in the status of natural resources. For example, expansion of agricultural production in some areas increases the potential for soil erosion, ground- and surface-water pollution, and loss of wildlife habitats.

Changes in precipitation and temperatures under doubled-CO_2 conditions favour irrigated crop production. Also, rising commodity prices from reductions in total output under the GFDL climate-change model enhance the feasibility of irrigation activities, particularly those associated with groundwater use. As a result, modelled irrigated crop acreage increases in most regions, as seen in Table 6. In the aggregate, the increases vary from 3.5 (GISS) to ~10.0 (GFDL) million acres. Regionally, major increases in irrigated acreage occur in the Northern Plains and in the Delta. The southeast is the only region that shows declines in irrigated acreage, due to the large increase in crop water-use forecast by the crop simulation models. The sustainability of any increase in irrigated acreage was not included in the analysis.

Discussion

Our results show a range of possible outcomes for US agriculture, depending on the severity of climate change and the compensating effects of CO_2 on crop yields. Changes in temperature and precipitation as forecast by the GCMs lead to reductions in yield and increases in crop water demands. As modelled here, increased atmospheric CO_2 enhances crop yields, mitigating some or all of the climate-induced yield changes. Under the most adverse case of climate change (GFDL), domestic and foreign consumers face moderate increases in real prices. These same price increases benefit US producers.

Some general implications for the US agricultural sector can be drawn. First, because of possible changes in domestic and foreign production under a GFDL climate, the role of the United States in agricultural export markets may change. Second, patterns of agriculture in the United States are likely to shift as a result of changes in regional crop yields and in crop irrigation requirements. Third, concern for future agricultural impacts on important natural resources, especially land and water, seems to be justified. Simulated irrigated acreage increases in most major irrigated regions under the models of climate change examined. In addition, irrigation may increase in more humid regions, a trend that is already occurring.

These results are a preliminary assessment of the potential effects of climate change on agriculture. Critical uncertainties remain, as does the question of appropriate action in light of uncertain but potentially important economic effects. We suggest three sets of considerations to pursue. First, policy makers need to assess whether the probability of the projected agricultural outcomes, coupled with the non-agricultural effects of climate change (for example, sea level rise, damage to natural ecosystems, and increased energy demand) warrant action now to plan for and to reduce the magnitude of climate change. Second, further research must be stimulated to understand likely crop yield, crop water demand and water supply as well as economic adjustments to climate change, thereby reducing the uncertainty of yield projections and other critical inputs to policy analyses. Better projections of changes in regional climate variables, particularly those affecting hydrological balances, are essential. Knowledge of potential change in global agricultural supply and demand is also crucial. Finally, it seems desirable that, for those regions (or countries) that may be adversely affected by climate change, research priorities be set on adapting varieties, species and production techniques to increased temperature and drought stress. □

Received 10 October 1989; accepted 1 March 1990.

1. Keeling, C., Bacastow, R. & Whorf, T. in *Carbon Dioxide Review: 1982* (ed. Clark, W.) 377–384 (Oxford University Press, 1982).
2. Ramanathan, V., Cicerone, R. J., Singh, H. B. & Kielhl, J. T. *J. geophys. Res.* **90,** 5557–5566 (1985).
3. Washington, W. M. & Meehl, G. A. *J. geophys. Res.* **89,** 9475–9503 (1984).
4. Hansen, J. *et al. J. geophys. Res.* **93,** 9341–9364 (1988).
5. Manabe, S. & Wetherald, R. T. *Science* **232,** 626–628 (1986).
6. National Research Council *Current Issues in Atmospheric Change* (National Academy Press, Washington, DC, 1987).
7. Schneider, S. H. *Science* **243,** 771–781 (1989).
8. Decker, W. L., Jones, V. & Achutuni, R. in *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health, Report DOW-ER-0236* (ed. White, M. R.) 69–93 (U.S. Department of Energy, 1985).
9. Schelling, T. C. in *Carbon Dioxide Assessment Committee, Changing Climate* 449–4985 (National Academy of Sciences, Washington, DC, 1983).

10. Smit, B., Ludlow, L. & Brklacich, M. *J. envir. Qual.* **17**, 519–527 (1988).
11. Rind, D., Rosenzweig, A. & Rosenzweig, C. *Nature* **334**, 483–486 (1988).
12. Sonka, S. T. & Lamb, P. J. *Clim. Change*, **11**, 291–311 (1987).
13. Parry, M. L., Carter, T. R. & Konijn, N. T. *The Impact of Climate Variation on Agriculture*, Vols 1 & 2 (Kluwer Academic, Norwell, 1988).
14. Hansen, J. *et al. Mon. Weath. Rev.* **3/4**, 609–622 (1983).
15. Kellogg, W. W. & Zhao, Z. *J. Clim.* **1**, 348–366 (1968).
16. Jones, J. W., Boote, K. J., Jagtap, S. S., Hoogenboom, G. & Wilkerson, G. G. *Florida Agricultural Experiment Station Journal* No. 8304, FAS (University of Florida, Gainesville) 1988).
17. Ritchie, J. T. & Otter, S. AGRISTARS publication No. YM-US-04442OJSC-18892 (Michigan State University, 1984).
18. Jones, C. A. & Kiniry, J. R. (eds) *CERES-Maise: A Simulation Model of Maize Growth and Development* (Texas A&M University Press, College Station, 1986).
19. Peart, B., Jones, J. W., Curry, R. B., Boote, K. J. & Allen, L. H. Jr in *The Potential Effects of Global Climate Change on the United States*, Appendix C (eds, Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
20. Ritchie, J. T., Baer, D. B. & Chou, T. W. *The Potential Effects of Global Climate Change on the U.S.* Appendix C (eds, Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
21. Rosenzweig, C. *The Potential Effects of Global Climate Change on the U.S.* Appendix C (eds, Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
22. Kimball, B. A. in *Carbon Dioxide Enrichment of Greenhouse Crops* (eds, Enoch, H. Z. & Kimball, B. A.) (CRL, 1986).
23. Rosenberg, N. J. *Clim. Change* **3**, 265–279 (1981).
24. Baker, J. T., Allen, L. H. Jr, Boote, K. J., Jones, P. & Jones, J. W. *Crop Sci.* **29**, 98–105 (1989).
25. Ramanathan, V. *Science* **240**, 293–299 (1988).
26. Adams, R. M., Glyer, J. D. & McCarl, B. A. in *The Potential Effects of Global Climate Change on the U.S.* Appendix C (eds, Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
27. Cheng, C. C. & McCarl, B. A. *The Agricultural Sector Model*, Texas Agricultural Experiment Station Misc. Report, College Station (in the press).
28. Adams, R. M., Hamilton, S. A. & McCarl, B. A. *Am. J. agric. Econ.* **68**, 886–894 (1986).
29. Adams, R. M. & Rowe, R. D. *J. envir. Manage.* (in the press).
30. Smith, J. B. & Tirpak, D. A. (eds) *The Potential Effects of Global Climate Change on the United States. Executive Summary* (US Environmental Protection Agency, Washington, DC, 1989).
31. Diewert, W. E. *J. Economet.* **4**, 116–145 (1976).

ACKNOWLEDGEMENTS. This work was funded in part by the US Environmental Protection Agency through interagency or cooperative agreements with NASA/Goddard Institute for Space Studies, Oregon State University, University of Florida and Michigan State University. We appreciate the help of J. Smith, D. Dudek, R. Goldberg, B. Baer, S. Johnson, R. House, M. Aillery, G. Schaible and T. Hickenbotham. We thank M. Brklacicha for review of an earlier version of this article.

Nuclear receptor that identifies a novel retinoic acid response pathway

David J. Mangelsdorf, Estelita S. Ong, Jacqueline A. Dyck* & Ronald M. Evans

Howard Hughes Medical Institute, The Salk Institute for Biological Studies, La Jolla, California 92138-9216, USA
* Physiology and Pharmacology Program, University of California, San Diego School of Medicine, San Diego, California 92093-0636, USA

Molecular cloning and transcriptional activation studies have revealed a new protein similar to the steroid hormone receptors and which responds specifically to vitamin A metabolites. This protein is substantially different in primary structure and ligand specificity from the products of the previously described retinoic acid receptor gene family. By indicating the existence of an additional pathway through which retinoic acid may exert its effects, these data lead to a re-evaluation of retinoid physiology.

THE retinoids comprise a group of compounds including retinoic acid, retinol (vitamin A), and a series of natural and synthetic derivatives that exert profound effects on development and differentiation in a wide variety of systems[1–8]. Retinoic acid has also been shown to induce the transcription of several genes[9], supporting the hypothesis that it functions in a fashion analogous to steroid and thyroid hormones (reviewed in refs 10, 11). Recently, a new member of the nuclear receptor superfamily was identified as a retinoic-acid dependent transcription factor, referred to as RARα (refs 12, 13). Subsequently, additional RAR-related genes have been isolated and at least three different RAR subtypes (α, β and γ) are now known in mice and humans[12–17]. These retinoic acid receptors (RARs) share homology with the superfamily of steroid hormone and thyroid hormone receptors and have been shown to regulate specific gene expression by a similar ligand-dependent mechanism[18]. The ligand-binding domains of these receptors are highly conserved (>75% amino acid identity), suggesting that they all arose from a common ancestral retinoic acid receptor. Nonetheless, these RAR subtypes are expressed in distinct patterns throughout development[19–21] and in the mature organism[13,15–17,22], indicating that they may mediate different functions. One important question is whether all the actions of retinoic acid are mediated through these proteins or whether additional retinoic acid substrates and regulatory networks exist.

Here we describe the molecular cloning and characterization of a gene for a novel or 'orphan' receptor and report that it encodes a 462-amino-acid polypeptide that functions as a transcription factor responsive to retinoic acid. Surprisingly, this retinoic acid receptor-like protein is not part of the previously described RAR-subfamily of receptors. These data demonstrate the existence of an evolutionarily parallel regulatory system through which retinoids may exert their control of transcription.

Orphan receptor

Sequential low-stringency screening of a human liver and kidney complementary DNA library with a cDNA fragment encoding the human (h)RARα DNA-binding domain led to the isolation of several cDNA clones encoding a novel nuclear receptor (referred to as hRXRα). The restriction map and nucleotide sequence of one of these clones, λXR3-1, are shown in Fig. 1. The λXR3-1 sequence contains a long open reading frame of at least 462 amino acids ending at the termination codon at nucleotide position 1,462–1,464. The presumptive initiation methionine is placed at the first in-frame ATG at nucleotide position 76–78, although an upstream termination codon is not present. A second potential initiator methionine occurs 27 amino acids downstream. The sequence surrounding both ATG sites conforms well with the consensus described by Kozak[23] for a translation initiation site. *In vitro* translation of RNA derived from the insert (data not shown) shows that λXR3-1 produces a protein of relative molecular mass 54,000 (M_r, 54 K), close to the predicted M_r of 50,811.

The amino-acid sequence of hRXRα has been compared with that of other members of the steroid hormone receptor superfamily (Fig. 2*a*). The highest degree of similarity between hRXRα and the other receptors is found in a cysteine-rich sequence of 66 amino acids beginning at hRXRα residue 135 (Fig. 1*b*). We have shown previously that this region of the human glucocorticoid receptor (hGR), thyroid hormone receptor (hTR) and retinoic acid receptor (hRAR) is the DNA-binding domain[11,18,24,25]. hRXRα shares striking similarity with the *Drosophila* receptor dXR2C8 (A. Oro, M. McKeown and R.E., manuscript in preparation), both in its DNA-binding (86%) and putative ligand binding (44%) domains. Although the RXRα DNA-binding domain is similar to that of other receptors such as RARα (61%) and TRβ (53%), the putative ligand-binding domain is much less similar (<27% identity) and provides no hint of the nature of the RXRα ligand. A comparison between